Cody Ray is studying mechanical engineering at Oregon State University, Corvallis, Oregon. He participated in the Science Undergraduate Laboratory Internship Program at Pacific Northwest National Laboratory, where he investigated "Power Grid Dynamics: Enhancing Power System Operation through Prony Analysis." As an undergraduate, he majored in applied mathematics at the University of Montana in Missoula. Mr. Ray is a member of the Society for Industrial and Applied Mathematics, the Mathematics Association of America, and PME. His hometown is Milton-Freewater, Oregon, and his interests include hiking, camping, and mathematical art.

Zhenyu Huang received his Ph.D. in electrical engineering from Tsinghua University, Beijing, China, in 1999. From 1998 to 2002, he conducted extensive research on power system analysis and control at McGill University (Canada), the University of Alberta (Canada), and the University of Hong Kong. He is currently a senior research engineer with the Energy Science and Technology Directorate, Pacific Northwest National Laboratory, Richland, Washington. His research interests include power system modeling and simulation, power system data analysis, and high performance computing applications. He is author of more than 40 peer-reviewed publications, and a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE).

POWER GRID DYNAMICS:
ENHANCING POWER SYSTEM OPERATION THROUGH PRONY ANALYSIS

CODY RAY AND ZHENYU HUANG

ABSTRACT

Prony Analysis is a technique used to decompose a signal into a series consisting of weighted complex exponentials and promises to be an efficient way of recognizing sensitive lines during faults in power systems such as the U.S. Power grid. Positive Sequence Load Flow (PSLF) was used to simulate the performance of a simple two-area-four-generator system and the reaction of the system during a line fault. The Dynamic System Identification (DSI) Toolbox was used to perform Prony analysis and use modal information to identify key transmission lines for power flow adjustment to improve system damping. The success of the application of Prony analysis methods to the data obtained from PSLF is reported, and the key transmission line for adjustment is identified. Future work will focus on larger systems and improving the current algorithms to deal with networks such as large portions of the Western Electricity Coordinating Council (WECC) power grid.

INTRODUCTION

Power system dynamics is highly complex. The number of interconnected nodes in the United States Power Grid exceeds any other man-made device on earth. It is the most complex system ever designed and is far from perfect. On August 10, 1996, the power grid had a massive blackout. A major system disturbance separated the Western Electricity Coordinating Council (WECC, formerly Western Systems Coordinating Council (WSCC)) system into four islands, interrupting service to 7.5 million customers for periods ranging from several minutes to about nine hours [1]. This very serious event led to an investigation of the reliability of the grid.

One of the outcomes from the investigation is the deployment of a Wide Area Measurement System (WAMS) across the WECC system. A WAMS network is a collection of Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDCs). WAMS provides high-speed GPS-time-synchronized phasor data, which can capture the dynamic behavior of a power grid.

One aspect of WAMS data analysis is to apply modal identification methods to identify major system oscillatory modes and damping information, which are excellent indicators of system stability status. PNNL (Pacific Northwest National Laboratory) has

been working with BPA (Bonneville Power Administration) for more than a decade developing algorithms and tools for WAMS data modal analysis. The Dynamic System Identification (DSI) Toolbox, jointly developed by PNNL and BPA, has been extensively used by many major power companies for WAMS data analysis, especially the Prony analysis function of this Toolbox.

With the modes and damping information, one would naturally ask what that information means to power system operators, in other words, how to use modal information to enhance power system operation.

This report summarizes initial results obtained working with power engineering researchers using modal information to identify key transmission lines for power flow adjustment to improve system damping. The results show that the method proposed and validated in this study is very promising.

This report is organized as follows: Basics of power system dynamics are first presented, followed by introductions to the methods and tools used in this study. The major part of the report is focused on the specific case studies and results, followed by a conclusion.

Power System Dynamics

Linearized form of power system dynamics can be described by a set of linear differential equations around an operation point:

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

$$(1)$$

The homogeneous ($u(t) = 0$) solutions of the system are a series of exponential terms, written as the following:

$$y(t) = \sum_{i=1}^{n} c_i e^{\lambda_i t} = \sum_{i=1}^{n} c_i e^{(-\sigma_i \pm j\omega_i)t} = \sum_{i=1}^{n} A_i e^{-\sigma_i t} \cos(\omega_i t + \phi_i) \quad (2)$$

In equation (2), λ_i are the eigenvalues of the system, also known as the dynamic modes of the object system, with ω being the oscillatory angular frequency and σ being the damping factor.

The damping ratio is defined as:

$$\xi = \frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \cdot 100\% \quad (3)$$

Damping ratios are a key indicator of system dynamic stability as follows:

$$\begin{cases} \xi > \xi_0 \rightarrow \text{Stable System} \\ 0 < \xi < \xi_0 \rightarrow \text{Poorly Damped System} \\ \xi < 0 \rightarrow \text{Unstable System} \end{cases} \quad (4)$$

TOOLS AND METHODS

There are many methods for analyzing a signal, especially one generated from a system such as the power grid. One can analyze the frequency of the grid, and how it changes due to fluctuations in the supply and demand of power. One can also monitor the voltage across sections of the grid. All of these signals, however, demand that one's methods of analysis deal with noise effectively. Noise usually plagues such signals so that any direct application of mathematical techniques is stricken with error as output. Thus, it is common to pre-filter a signal with methods designed to reduce noise, smooth the signal, and yet retain important data. In reality, even the best filtering techniques fail to completely eliminate noise from the signal.

Two very important mathematical methods for understanding such a system are Fourier and Prony analysis (Figure 1). There are fundamental differences in how these methods are implemented and analyzed.

Fourier analysis, implemented with the fast Fourier transform (FFT), is a relatively fast operation. It can be used to dissect a signal into its constituent frequency components, approximating the phase, amplitude, and frequency of the components in the signal. Fourier analysis offers both a deep understanding of a signal and can be implemented in a powerful filtering algorithm.

Prony analysis also dissects a signal into many components, each consisting of an amplitude, phase and frequency, but goes further to estimate the damping coefficients of the signal. Thus Prony analysis is best suited to a system experiencing damping.

The DSI Toolbox is used to perform Prony analysis throughout this study. Positive Sequence Load Flow (PSLF), General Electric's

tool for power system dynamic simulation, was used to generate power system signals simulating a sample power grid stimulated by disturbances.

Prony Analysis

Prony analysis decomposes signals into damped sinusoidal waveforms, so the modes can be determined.

$$y(t) = \sum_{i=1}^{q} 2B_i e^{-\sigma_i t} \cos(\omega_i t + \varphi_i) = \sum_{i=1}^{q} A_i e^{(-\sigma_i \pm j\omega_i)t} \quad (5)$$
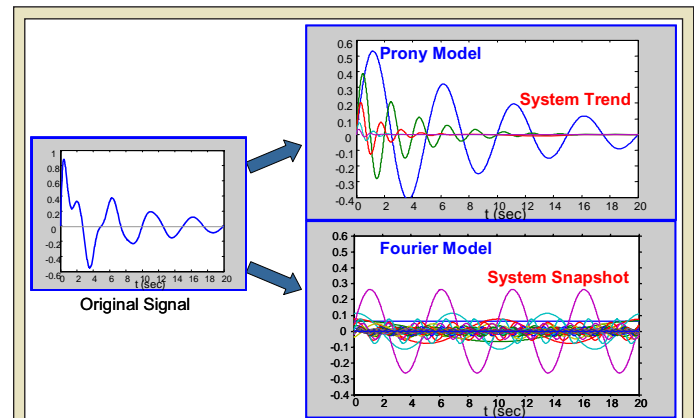

Figure 1. Prony analysis vs. Fourier analysis.

In comparison with Equation (2), Prony analysis results can be used to determine the key parameters of the system dynamics. With high-speed phasor measurement data, Prony analysis can be performed in a real-time manner, and system stability characteristics can be determined in real-time as well. This has been a monitoring function in industrial practice. Figure 2 shows an example of Prony analysis applied to the measured data of the 10 August 1996 western system blackout. One can see that after the first sign of system deterioration, there were about 6 minutes before the system broke up.

The Power System Monitoring (PSM) Toolset, or PSMtools, is a collection of processing utilities that is contained within the Dynamic System Identification (DSI) Toolbox developed by the Bonneville Power Administration (BPA) and the Pacific Northwest National Laboratory (PNNL). The DSI Toolbox is a Matlab version of BPA systems analysis tools that trace their origins to wide area control projects in the mid 1970's, and that have undergone extensive use and refinement since that time [1]. The DSI Toolbox contains Prony analysis tools, which are capable of importing data created by PSLF.

Research Plan

Can modal information by utilized for control and operation purposes? That is the fundamental question in this research. For the 10 August 1996 event, what should have been done during the 6 minutes shown in Figure 2? Using Prony analysis, the signal can be decomposed into a series of signals containing mode, damping, and amplitude information (see Figure 1). This study explores the capability of using the modal information to enhance power system operations.

Figure 2. Prony analysis of the August 10 1996 western system breakup event.
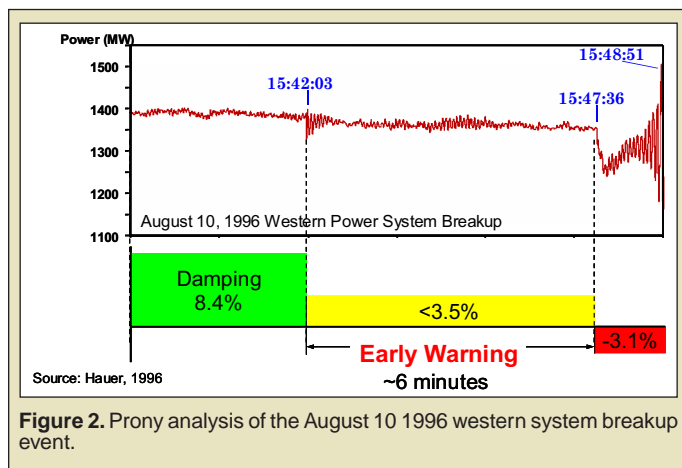
Low damping is typically caused by long-distance heavy power transfer, which means a heavily stressed transmission system. Once low damping is detected/observed, one can re-dispatch generation or adjust load in certain areas to reduce system stress. Prony analysis provides residual information together with modal information. Residual information can serve as indicators of the sensitivity of the quantity with respect to the mode. This residual information can then be used to identify critical components where power transfer should be adjusted to improve damping.

Case Creation

A simple two-area-4-generator model [3] was obtained for use in PSLF. The model is shown in Figure 3. A baseline 1767MW load at bus 13 was used with output from each generator being about 700MW, as the model was stable at this point. Trial and error yielded an upper bound for oscillatory behavior, which was approximately +79MW change in generation and load. Each case was created by incrementing the generation of G1 by 15.8MW (= 79MW/5), and also increasing/decreasing the load on bus 13 by the same amount. So there are 11 resulting cases including the original base case. This new model was then allowed to run for one second. At one second, the system experienced a programmed line fault at bus 3 for 0.05 seconds. The fault was then cleared and the simulation was allowed to run for another 20 seconds. The resulting data was then exported, using a script, to a file that the DSI toolbox could import.

Figure 3. A simple 4 generator, two-area system.
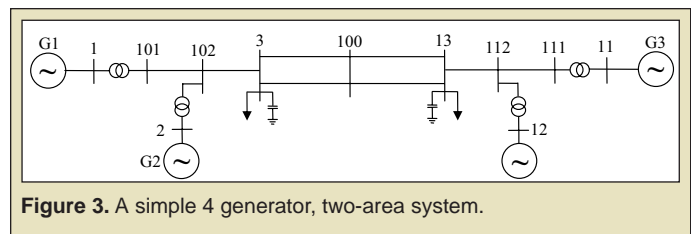
RESULTS

The 11 cases are simulated using PSLF. Each case has a different loading level and exhibits different dynamic behavior. In this section, the time-domain dynamic simulation results and the frequency-domain Prony analysis results (modal information) are presented. These cases test the possibility of using modal information to improve power system operation.

The simulation yielded very different behavior for each case. As shown in Figure 4, the upper-limit increase of 79MW in load and generation resulted in an unstable system, with high frequency oscillations. This contrasts with the increase of only 15.8MW, in which a barely noticeable oscillation occurs immediately following the line fault, but is then damped out quickly, resulting in a stable system.

Figure 4. Difference in dynamics among cases.
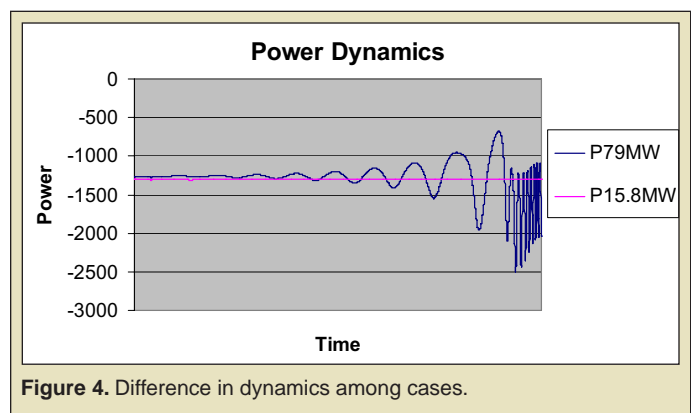
The oscillatory behavior results from a system that is over stressed or has too much power being transferred between areas. A system that becomes unstable following an event like the line fault in our simulation, can lead to terribly damaging consequences. Power grids can also experience this behavior; in fact there are oscillations constantly occurring in real systems. Most of these are small with respect to the overall size of the grid and are quickly damped out. A very large scale event however, such as the tripping of an entire generator, can result in a situation similar to the 79MW case. Currently, one way to prevent the entire system from becoming unstable is to dispatch load or generation in key areas to lead to a high damping coefficient for the system. Prony analysis can add insight into what areas are most sensitive.

Damping ratios are correlated with changes in load/generation, with the overall damping ratio decreasing with more load and generation and hence greater system stress. Thus, as the power is increased in this system, the ability of the system to reach stability after a fault is compromised. This agrees with Figure 4; the system

becomes more unstable with heavier load and generation. The larger the event, the more unlikely the system will naturally damp out the dangerous oscillations that occur. This emphasizes the importance for finding a method of recognizing key lines/areas within a system that, when adjusted, can result in higher damping coefficients and thus a more stable system.
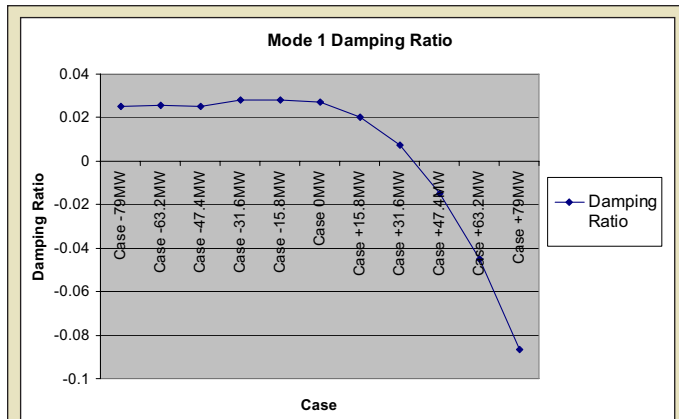

Figure 5. Damping Ratio vs. Case.

Prony analysis yields residue information that can be used to identify important lines that the overall modal information depends upon. Thus, these lines are the key lines to adjust to increase stability in the time of an event. Figure 6 shows a plot of the amplitude of the residue information for each line in each case. It readily becomes obvious that line 13-112 has the greatest amplitude, and thus must be of great importance.
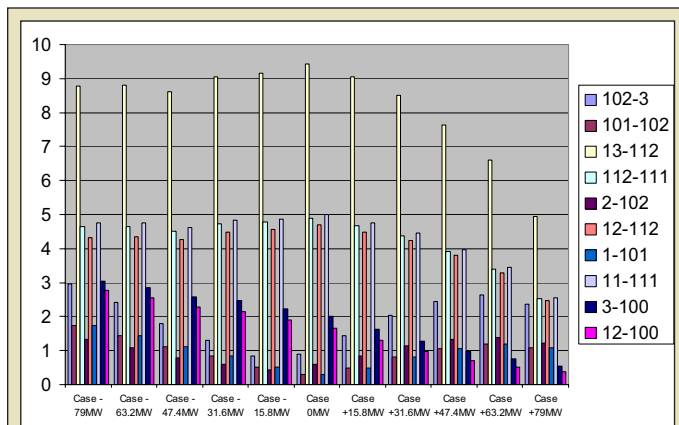

Figure 6. Residue magnitudes vs. lines for each case.

After this insight is obtained, another plot of the overall system damping ratio versus the key line loading further suggests this line is of the utmost importance in the stability of this system. Figure 7 displays a strongly correlated plot between system damping and key line loading. This is another strong indication that the damping ratio could be affected by adjustments on this line.
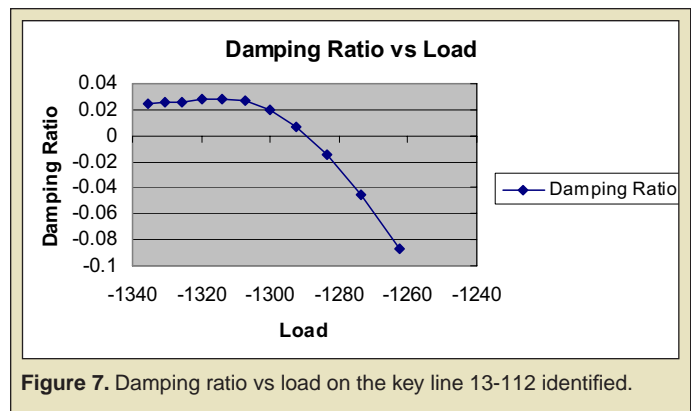

Figure 7. Damping ratio vs load on the key line 13-112 identified.

The data from each case strongly correlates the damping ratio to load levels. Using the residue information output from Prony analysis, every case yields the same result: the line most sensitive to changing load and generation is line 13-112 (see Figure 6). This line is therefore the most important as far as overall system stability. Adjusting the loading on this line would help to damp the inter-area oscillations between the two areas.

CONCLUSION

New tools such as Prony analysis, coupled with simulation models and already existing techniques, are enormously useful for interpreting data from systems such as the simple system used in this research. The next step is to apply the techniques used above to larger systems, with complexity great enough to preclude intuitive human responses (such as the IEEE 14 bus system and the WECC system). A system such as the WECC power grid is entirely too complex for crude adjustments based on intuition and past experience. Prony analysis and the resulting modal and residual information obtained could greatly increase the ability to decide what lines/areas to adjust to prevent a cascading failure of the system.

ACKNOWLEDGMENTS

REFERENCES

[1]   J. F. Hauer, PSMtools: Matlab Utilities for Processing of Power System Response Records.

[2]   W.S.C.C. Disturbance Report for August 10th, 1996 15:48 PAST.

[3]   P. Kundur, "Power System Stability and Control", McGraw-Hill, 1994.